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Empirical Approach to Satellite Snow Detection

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ACADEMIC DISSERTATION in meteorology

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Nimeke

Empiirinen lähestymistapa satelliittilumentunnistukseen

Tiivistelmä

Lumipeitteellä on huomattava vaikutus säähän, ilmastoon, luontoon ja yhteiskuntaan. Pelkästään sääasemilla tehtävät lumihavainnot (lumen syvyys ja maanpinnan laatu) eivät anna kattavaa kuvaa lumen peittävyydestä tai muista lumipeitteen ominaisuuksista.

Sääasemien tuottamia havaintoja voidaan täydentää satelliiteista tehtävillä havainnoilla. Geostationaariset sääsatelliitit tuottavat havaintoja tihein välein, mutta havaintoresoluutio on heikko monilla alueilla, joilla esiintyy kausittaista lunta. Polaariradoilla sääsatelliittien havaintoresoluutio on napa-alueiden läheisyydessä huomattavasti parempi, mutta silloinkaan satelliitit eivät tuota jatkuvaa havaintopeittoa. Tiheimmän havaintoresoluution tuottavat sääsatelliittiradiometrit, jotka toimivat optisilla aallonpituuksilla (näkyvä valo ja infrapuna).

Lumipeitteen kaukokartoitusta satelliiteista vaikeuttavat lumipeitteen oman vaihtelun lisäksi pinnan ominaisuuksien vaihtelu (kasvillisuus, vesistöt, topografia) ja valaistusolojen vaihtelu. Epävarma ja osittain puutteellinen tieto pinnan ja kasvipeitteen ominaisuuksista vaikeuttaa luotettavan automaattisen analyyttisen lumentunnistusmenetelmän kehittämistä ja siksi empiirinen lähestymistapa saattaa olla toimivin vaihtoehto automaattista lumentunnistusmenetelmää kehitettäessä.

Tässä työssä esitellään kaksi EUMETSATin osittain rahoittamassa H SAFissa kehitettyä lumituotetta ja niissä käytetyt empiiristä lähestymistapaa soveltaen kehitetyt algoritmit. Geostationaarinen MSG/SEVIRI H31 lumituote on saatavilla vuodesta 2008 alkaen ja polaarituote Metop/AVHRR H32 vuodesta 2015 alkaen. Lisäksi esitellään pintahavaintoihin perustuvat validointitulokset, jotka osoittavat tuotteiden saavuttavan määritellyt tavoitteet.

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Empirical Approach to Satellite Snow Detection

Abstract
Snow cover plays a significant role in the weather and climate system, ecosystems and many human activities, such as traffic. Weather station snow observations (snow depth and state of the ground) do not provide high-resolution continental or global snow coverage data.
The satellite observations complement in situ observations from weather stations. Geostationary weather satellites provide observations at high temporal resolution, but the spatial resolution is low, especially in polar regions. Polar-orbiting weather satellites provide better spatial resolution in polar regions with limited temporal resolution. The best detection resolution is provided by optical and infra-red radiometers onboard weather satellites.
Snow cover in itself is highly variable. Also, the variability of the surface properties (such as vegetation, water bodies, topography) and changing light conditions make satellite snow detection challenging. Much of this variability is in subpixel scales, and this uncertainty creates additional challenges for the development of snow detection methods. Thus, an empirical approach may be the most practical option when developing algorithms for automatic snow detection.
In this work, which is a part of the EUMETSAT-funded H SAF project, two new empirically developed snow extent products for the EUMETSAT weather satellites are presented. The geostationary MSG/SEVIRI H32 snow product has been in operational production since 2008. The polar product Metop/AVHRR H32 is available since 2015. In addition, validation results based on weather station snow observations between 2015 and 2019 are presented. The results show that both products achieve the requirements set by the H SAF.

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To my family:
Pilvi
Kaisla
Oula
Sameli
Hilla

PREFACE

I have always wanted to be a scientist. At first, theoretical physics was tempting, but it turned out to be too theoretical. Then, a friend said that I should change to geophysics because there are field trips. I managed to get a degree and soon after I got a job at the Department of Meteorology of the University of Helsinki: sea ice remote sensing or something like that. Some years later, I got a new job at the FMI, but UV-database development was not as exciting as promised. It was time to move on to remote sensing of snow. I'm still sitting in the office (at home for the last six months), but, at least, there have been some snow pits on the way.

This work has progressed at a slow and not that steady pace. In the beginning, there were no deadlines. Now, there are doctoral schools, expiration times, and the thesis is just the beginning. I'm probably a relic from the old world, but I managed to finish in less than 25 years. I want to thank my latest supervisors Otto Hyvärinen and Heikki Järvinen for their advice and patience during these years. I also would like to thank my earlier supervisors who have retired or changed positions.

I want to thank the members of the Satellite and Radar Applications group and the fine folks from the coffee breaks. Especially, I am grateful to my Head of Group Terhikki Manninen for her advice and support. I wish to thank the people at the Numerical Weather Prediction group for their comments and suggestions. I want to thank my colleagues at the FMI Meteorological Research and, of course, my co-authors.

During the years, I have been supported by the staff of the LSA SAF and H SAF. I'm grateful for the discussions with Samantha Pullen and others at the Met Office. The Finnish Meteorological Institute has provided an excellent working environment during the last 20 years.

There is also life outside of work. I wish to thank my dear friends Merikki and Esa who have been moving farther and farther away but never too far for a phone call. Timo has always been able to suggest interesting and funny films, TV shows, books and games. Of course, I want to thank all my other friends near and far (if that rings any bells).

And then there are the relatives. I want to thank my parents and sisters and their families and also my wife's parents and sisters. Finally, and most importantly, I would like to thank my family: my wife Pilvi for her patience and support and my children Kaisla, Oula, Sameli and Hilla for just being there. My life would have been pretty dull and boring without all of you.

Niilo Siljamo
Helsinki, 2020

CONTENTS

LIST OF ACRONYMS

AVHRR	Advanced Very High Resolution Radiometer
ECMWF	European Center for Medium-Range Weather Forecasts
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FCI	Flexible Combined Imager
EO-1	Earth Observing-1
FMI	Finnish Meteorological Institute
GAC	Global Area Coverage
GOES	Geostationary Operational Environmental Satellite system
H SAF	SAF on Support to Operational Hydrology and Water Management
IMS	Interactive Multisensor Snow and Ice Mapping System
H31	H SAF MSG/SEVIRI Snow Extent
H32	H SAF Metop/AVHRR Snow Extent
HRV	High Resolution Visible
JPSS	Joint Polar Satellite System
LSA SAF	SAF for Land Surface Analysis
LST	Land Surface Temperature
METimage	Meteorological Imager
MODIS	Moderate Resolution Imaging Spectroradiometer
MSG	Meteosat Second Generation
MTG	Meteosat Third Generation
Metop-SG	Meteorological Operational Satellite - Second Generation
Metop	Meteorological Operational Satellite
NDSI	Normalized-Difference Snow Index
NESDIS	National Environmental Satellite, Data, and Information Service
IR	Infrared Radiation
NIR	Near-Infrared Radiation
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
NWP	Numerical Weather Prediction
PDU	Product Dissemination Unit
SAF	Satellite Application Facility
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SMHI	Swedish Meteorological and Hydrological Institute
SNORTEX	Snow Reflectance Transition Experiment
SWE	Snow Water Equivalent

SWIR	Short-Wavelength Infrared Radiation
VIIRS	Visible Infrared Imaging Radiometer Suite
VISSR	Visible and Infrared Spin Scan Radiometer

LIST OF ORIGINAL PUBLICATIONS AND AUTHOR'S CONTRIBUTION

I N. Siljamo and O. Hyvärinen (June 2011). 'New Geostationary Satellite-Based Snow-Cover Algorithm'. *J. Appl. Meteor. Climatol.* **50**:6, pp. 1275–1290. DOI: 10.1175/2010JAMC2568.1

In Paper **I**, the author developed the algorithms and took part in validation of the product. The author wrote most of the paper.

II N. Siljamo, O. Hyvärinen, A. Riihelä and M. Suomalainen (2020). 'Metop/AVHRR snow detection method for meteorological applications'. *J. Appl. Meteor. Climatol.* Submitted February 2020

In Paper **II**, the author was responsible for development of the algorithms, validation of the product, making most of the visualizations and writing most of the paper.

III I. F. Trigo, C. C. Dacamara, P. Viterbo, J.-L. Roujean, F. Olesen, C. Barroso, F. Camacho-de-Coca, D. Carrer, S. C. Freitas, J. Garcia-Haro, B. Geiger, F. Gellens-Meulenberghs, N. Ghilain, J. Meliá, L. Pessanha, N. Siljamo and A. Arboleda (2011). 'The Satellite Application Facility for Land Surface Analysis'. *Int. J. Remote Sens.* **32**:10, pp. 2725–2744. DOI: 10.1080/01431161003743199

In Paper **III** the author was responsible for writing most of the section describing snow products and providing the snow product validation results.

IV O. Hyvärinen, K. Eerola, N. Siljamo and J. Koskinen (2009). 'Comparison of snow cover from satellite and numerical weather prediction models in Northern Hemisphere and northern Europe'. *J. Appl. Meteor. Climatol.* **48**:6, pp. 1199–1216. DOI: 10.1175/2008JAMC2069.1

In Paper **IV**, the author took part in the writing and provided the LSA SAF data.

V K. Anttila, T. Manninen, T. Karjalainen, P. Lahtinen, A. Riihelä and N. Siljamo (2014). 'The temporal and spatial variability in submeter scale surface roughness of seasonal snow in Sodankylä Finnish Lapland in 2009–2010'. *J. Geophys. Res. Atmos.* **119**: pp. 9236–9252. DOI: 10.1002/2014JD021597

In Paper **V**, the author took part in the field measurements during the SNORTEX campaign and had a minor part in the writing.

1 INTRODUCTION

1.1 MOTIVATION

Weather has a large impact on society, the economy and everyday life of the people. For that reason, people have been trying to forecast weather for thousands of years. Weather forecasting based on science began when the speed of communication reached the level which allowed collecting observations from larger areas.

Later, the invention and development of computers allowed Numerical Weather Prediction (NWP). Modern NWP is based on large masses of observations of weather and surface parameters which are used in determining the initial state for the weather models (i.e. data assimilation). As it is said by Pullen et al. (2010), snow is an extremely important component of the land surface system. While it has a large impact on many radiative and hydrological properties, especially important is the way snow changes the surface albedo.

Snow has a strong impact on ecosystems, as well (Niittynen et al. 2018). The importance of snow is quite well summarized in the short *Nature Climate Change* editorial ‘Let it snow’ (2018): "The changing nature of snow under anthropogenic warming — including coverage, duration and melt characteristics — stands to exert substantial impacts across physical, biological and socio-economic systems. However, our understanding of these impacts is often constrained by inadequate snow observations, limited in both spatial and temporal resolution."

Changes in snow cover can have drastic effects on the surface properties and the energy and mass balance on the surface. For example, snow has a much higher albedo than snow-free surfaces, which changes the shortwave radiation flux when a larger part of the incoming radiation is reflected from the surface. Snow also behaves as temporary water storage (measured as Snow Water Equivalent (SWE)) as falling snow stays on the surface until the snow melts and the water runs off. The phase changes between vapour, liquid and solid forms release or absorb energy. The physical properties of the snow cover change over time (grain size, density, snow depth and so on). Snow cover and its properties are discussed in more detail in, for example, the recent thesis by Leppänen (2019).

At the same time, snow cover is very variable both spatially and temporally. Snowfall may be very uneven by itself and also other weather conditions may change the way snow accumulates. For example, wind may create large snowdrifts and move the snow away from other places. On the other hand, melting snow cover is often uneven and patchy as melting advances faster in some spots and slower in others. Still, even a thin snow layer changes the surface properties. Differences in e.g. topography and vegetation (especially forests) can change the development of the snow field. Especially in the margin of the snow-covered area, snow may appear and disappear rapidly.

Because snow-covered and snow-free surfaces have different properties, information about snow coverage would be beneficial for many applications. Usually, necessary observations can be obtained from synoptic weather stations, which, however, may be far from each other especially in uninhabited remote areas. Often, the only available snow measurement from a weather station is snow depth. While suitable for many applications, it does not say much about snow coverage, especially when the snow depth is small or snow cover is not continuous.

As a further hindrance, snow depth is often not reported from snow-free weather stations. This is unfortunate because there are weather stations which do not measure snow depth at all and these two cases are essentially impossible to distinguish from each other.

Even though weather observations from weather stations, radiosondes, ships, buoys and aeroplanes are a necessary part of the modern weather forecasting, there are still large gaps in the observation networks, especially in remote areas and oceans. These can be partly covered by remote sensing methods, such as radars and satellites which provide excellent but usually indirect observations in good spatial and temporal resolution for many kinds of applications. There are organizations (such as European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), National Oceanic and Atmospheric Administration (NOAA)) which operate weather satellites specifically for this purpose.

On the surface, the general features of the snow cover are easy to see by any observer. In open areas, including grasslands and other areas without trees or shrubs, the surface can be snow-free, completely snow-covered or more or less partially snow-covered. From satellites, open areas are relatively easy targets even though vegetation can be a challenge when the snow depth is small or snow cover is patchy.

On the other hand, in forests and shrublands snow cover should be considered in two parts, snow on the surface and snow on the canopy, which can both be snow-covered or snow free. In typical weather satellite resolutions, these two may be difficult to handle separately. Thus, a satellite pixel classified as fully snow-covered may be snow-covered on the surface, on trees or both.

Some weather stations observe and report the state of the ground (defined in WMO 2015), which can be interpreted as an estimated snow coverage (no snow, less than half, over half, full snow cover). Unfortunately, at the moment these observations are only available from manned stations which are expensive to operate and are often replaced with automatic weather stations.

Typically, weather satellite radiometers measure the radiation on a few separate radiation bands. In general, older but still operational weather satellite instruments (e.g., Advanced Very High Resolution Radiometer (AVHRR)) provide data on 4–5 bands or channels, while more modern instruments (such as Visible Infrared Imaging Radiometer Suite (VIIRS)) may provide 10–25 channels or even more. For research purposes, hyperspectral instruments, such as Hyperion onboard the Earth Observing-1 (EO-1) satellite, which provides 220 channels, can provide excellent data.

Even though both snow and clouds as seen from space are quite similar in the visible parts of the spectrum, there are clear differences in the Infrared Radiation (IR) wavelengths. An example of this is shown in the image pair in Fig. 1, which covers southern parts of the UK one day after heavy snowfall on December 10, 2017. Heavy snowfall caused material damages, traffic delays and hundreds of school closures. Two different versions of the same Suomi-National Polar-orbiting Partnership (NPP)/VIIRS scene are presented. In the true colour image, both snow and clouds appear practically white, even though for human observer there are subtle differences in the structural patterns. Snow and clouds are slightly different when IR channels are employed. Even though for human analysts the differences are easy to recognize, it is quite a complicated task to convert that knowledge to a format suitable for computers.

Clouds and snow are usually both highly reflective in the visible band of the electromagnetic spectrum, but in Near-Infrared Radiation (NIR) or Short-Wavelength Infrared Radiation (SWIR) bands snow is highly absorptive, as seen in Fig. 2. Normalized-Difference Snow Index (NDSI), which is defined as:

$$\mathrm{NDSI} = \frac{R_{\mathrm{visible}} - R_{\mathrm{IR}}}{R_{\mathrm{visible}} + R_{\mathrm{IR}}},$$

where R_{visible} is reflectance on the visible band and R_{IR} reflectance on the IR band, is based on this difference. Depending on the instrument and the measuring bands available, pixels which are highly reflective on visual bands (either snow or clouds) can be classified as snow-covered if the NDSI value is over a suitable threshold and snow-free if NDSI is lower than the threshold.

NDSI or similar ratios have been used for snow detection quite a long time (Hall and Riggs 2011). However, NDSI snow detection needs improvements in local scale (discussed e.g., in Härer et al. 2018). In ideal conditions, NDSI provides good results, but in practice, the conditions are often far from ideal. For that same reason, reliable modelling of the radiative properties of the snow cover is difficult. In operational systems, there may be timeliness requirements which prevent the use of complicated and time-consuming methods. Therefore, an empirical approach can be beneficial in satellite snow detection.

In Europe, EUMETSAT is the organization responsible for the operating of the weather satellites. It operates both geostationary (e.g. Meteosat Second Generation (MSG)) and polar-orbiting (Meteorological Operational Satellite (Metop))

Figure 1 *Example images from Suomi-NPP/VIIRS for December 11, 2017, one day after heavy snowfall in large parts of the UK. On the top left true colour corrected reflectance, on the top right corrected reflectance for bands M3-I3-M11 (490-1610-2250 nm). Snow and clouds appear white on the left, but on the right the snow is bright red, clouds either white or pink. On the bottom, a view towards west from the top of The Beacon in Malvern, UK, which is located in the middle of the snow-covered area seen on the top. Suomi-NPP/VIIRS images by NASA Worldview. Photo: Niilo Siljamo (NS).*

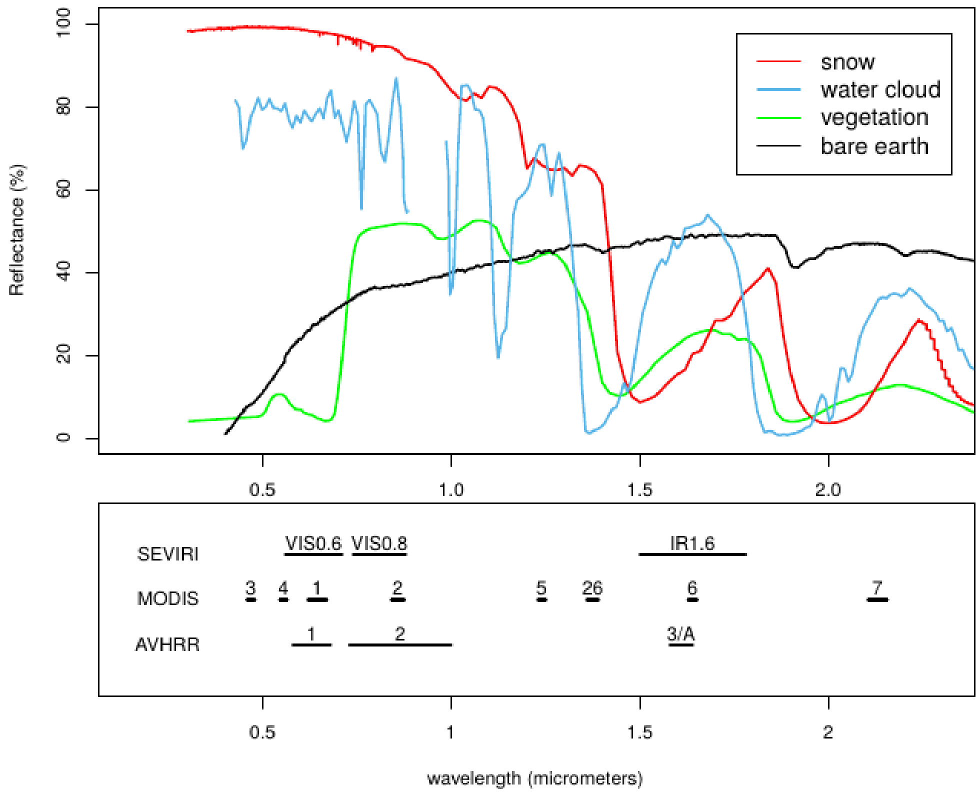

Figure 2 *A rough sketch of the spectral reflectances of common ground types and a water droplet cloud with the channels of common meteorological satellite instruments. The reflectances of ground types are based on Baldridge et al. (2009) and the reflectance of a water cloud is based on an arbitrary image taken on 12 June 2010 02:08 UTC near Barbourville, Kentucky, United States using the hyperspectral Hyperion instrument onboard the EO-1 satellite. (Image from Hyvärinen 2011)*

weather satellites. It provides data and products based on satellite data for many applications from the EUMETSAT Central Facility. In addition, there are several Satellite Application Facilities (SAFs), which are a distributed network of partly EUMETSAT funded consortiums responsible for operational, research and development activities (EUMETSAT 2020). They develop and produce additional products for specific user groups. For example, SAF on Support to Operational Hydrology and Water Management (H SAF) produces snow (such as SWE and snow extent), soil moisture and precipitation products. SAF for Land Surface Analysis (LSA SAF) provides shortwave and longwave radiation, albedo, wildfire, vegetation and Land Surface Temperature (LST) products. The SAFs focus on the use of the EUMETSAT satellite data, but in some applications, other data is used as well. The satellite snow product development and validation presented in this thesis has been done at first as part of the LSA SAF and later in the H SAF.

1.2 PREVIOUS RESEARCH

Remote sensing satellites can be used to cover the gaps in snow coverage observations. Even though the spatial resolution of the typical weather satellites is not suitable for high-resolution (about 100 m or better) snow coverage observations, at least the presence of snow can be detected. There are many previously published snow products and algorithms for different instruments onboard different satellites each with different purposes and merits (see e.g., **Paper II**). Several binary (snow/no snow) satellite snow products are available and there are also some fractional snow cover products developed e.g., by Metsämäki et al. (2012).

One well-known snow product is the Interactive Multisensor Snow and Ice Mapping System (IMS) which is provided by NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) (Helfrich et al. 2007; Ramsay 1998), which is a high-resolution multisensor snow product. The IMS product is not based on a fully automatic algorithm; instead, the production employs human analysts who merge data from many different sources, including *in situ* data. Some validation results for IMS are presented in Chen et al. (2012).

There are many cryosphere products for polar-orbiting satellites operated e.g., by NOAA and EUMETSAT. As part of the AVHRR processing packages, there are often snow products (e.g., Dybbroe et al. 2005). Another method is suggested by Hüsler et al. (2012) for snow detection over the European Alps.

Snow products based on Moderate Resolution Imaging Spectroradiometer (MODIS) data have been described by e.g., Miller et al. (2005) and Notarnicola et al. (2013a,b). MODIS instruments are onboard the *Terra* and *Aqua* satellites which are nearing the end of their lifetime. MODIS will be superseded in many applications by the VIIRS onboard the NPP and the Joint Polar Satellite System (JPSS) satellites which have similar channels suitable for snow detection as MODIS (Miller et al. 2006). A snow product for VIIRS is published by Key et al. (2013). More details of the VIIRS snow detection are presented in Riggs et al. (2015). Riggs et al. (2017) describes both MODIS and VIIRS snow cover products. Snow products based on multiple instruments are presented e.g. by Hori et al. (2017) where an algorithm, product for AVHRR and MODIS and validation results from 38 years are presented.

There are also some projects which provide or plan to provide snow products based on one or more satellite instruments (e.g., CryoClim (Solberg et al. 2009) and ESA CCI Snow (Wunderle et al. 2019)). The main product is often SWE, but also snow extent products are provided.

For other polar-orbiting instruments, Selkowitz and Forster (2015) presents a method for automatic mapping of persistent ice and snow for Landsat TM and ETM+. There is also a similar Sentinel program. Both Landsat and Sentinel have a repeat interval of several days which limits their use in daily snow detection.

Geostationary orbit does not provide good coverage in polar regions, but there are several satellites (such as Geostationary Operational Environmental Satellite system (GOES), Meteosat, FY-2, Himawari) with instruments which are well-suited for snow detection in mid-latitudes. Romanov et al. (2003) use GOES data for snow fraction detection and Li et al. (2007) uses it for snow and cloud detection. For MSG/Spinning Enhanced Visible and Infrared Imager (SEVIRI), there are several snow extent products, such as the one presented in **Paper I** (H SAF MSG/SEVIRI Snow Extent (H31)). Wang et al. (2017) suggest a fractional snow cover product for the FY-2 Visible and Infrared Spin Scan Radiometer (VISSR).

There are also other satellite instruments which can be used for satellite snow detection. For example, microwave radiometers are often used for snow products. While microwave radiometers do not require external illumination (i.e., sunlight) and cloud cover is transparent in microwave wavelengths, the spatial resolution of the microwave radiometers is quite coarse (10–15 km or more) when compared to visible and IR band radiometers. Also, microwave radiometers struggle with thin snow layers, especially in wet conditions, (Takala et al. 2009) and that is a limiting factor in meteorological applications where even a thin snow layer should be detected.

Quite often the primary snow product available is not snow extent or snow detection product. Other products can be used to estimate snow coverage with limitations. For example, SWE products such as the one presented by Takala et al. (2011), may need ancillary data in the product generation (in this case weather station snow observations).

In a recent paper, Walters et al. (2019) describe shortly the snow model used in the Met Office Unified Model and the Joint UK Land Environment Simulator. Recent developments of introducing the H31 product (the product described in **Paper I**) into that system was presented by Pullen et al. (2019). Similar trials using a variant of the H SAF Metop/AVHRR Snow Extent (H32) product are underway at the Finnish Meteorological Institute (FMI).

1.3 THIS THESIS

The aim of this work was to develop daily operational satellite snow detection products for optical radiometers onboard the EUMETSAT MSG and Metop satellites as part of the LSA SAF and later the H SAF. During this work, two new snow detection methods were developed.

In the MSG satellites (pictured in Fig. 3), the radiometer is SEVIRI, which has 12 channels in optical and IR bands. In the first generation Metop satellites (Fig. 4), AVHRR is used. It has only 6 channels in optical and IR bands and channels 3A and 3B can not be used simultaneously. The properties of both AVHRR and SEVIRI channels are presented in Table 1.

These two different satellite snow detection products and algorithms used in processing them are presented in **Papers I** and **II**. These products were developed as part of the EUMETSAT-funded projects (SAFs) where the author has been responsible for the development of the snow detection products based on visual and IR channels. The products the author has been developing are targeted for operational meteorological applications, such as NWP where the accuracy of data is

Table 1 *AVHRR and SEVIRI channels and frequencies. AVHRR resolution in nadir is 1.1 km. AVHRR channels 3A and 3B are not available at the same time. SEVIRI resolution in nadir is 3 km. SEVIRI channel 12 is a so-called High Resolution Visible (HRV) broadband channel which has a 1 km resolution. The channels used in the H SAF MSG/SEVIRI H31 (1, 2, 3, 4, 9, 10) and H SAF Metop/AVHRR H32 (1, 2, 3A, 4, 5) algorithms are in bold.*

Metop/AVHRR		MSG/SEVIRI	
Channel	Frequency (μm)	Channel	Frequency (μm)
1	**0.58 – 0.68**	**1**	**0.56 – 0.71**
2	**0.727 – 1.00**	**2**	**0.74 – 0.88**
3A	**1.58 – 1.64**	**3**	**1.50 – 1.78**
3B	3.55 – 3.93	**4**	**3.48 – 4.36**
		5	5.35 – 7.15
		6	6.85 – 7.85
		7	8.30 – 9.10
		8	9.38 – 9.94
4	**10.30 – 11.30**	**9**	**9.80 – 11.80**
5	**11.50 – 12.50**	**10**	**11.00 – 13.00**
		11	12.40 – 14.40
		12 (HRV)	0.4 – 1.1

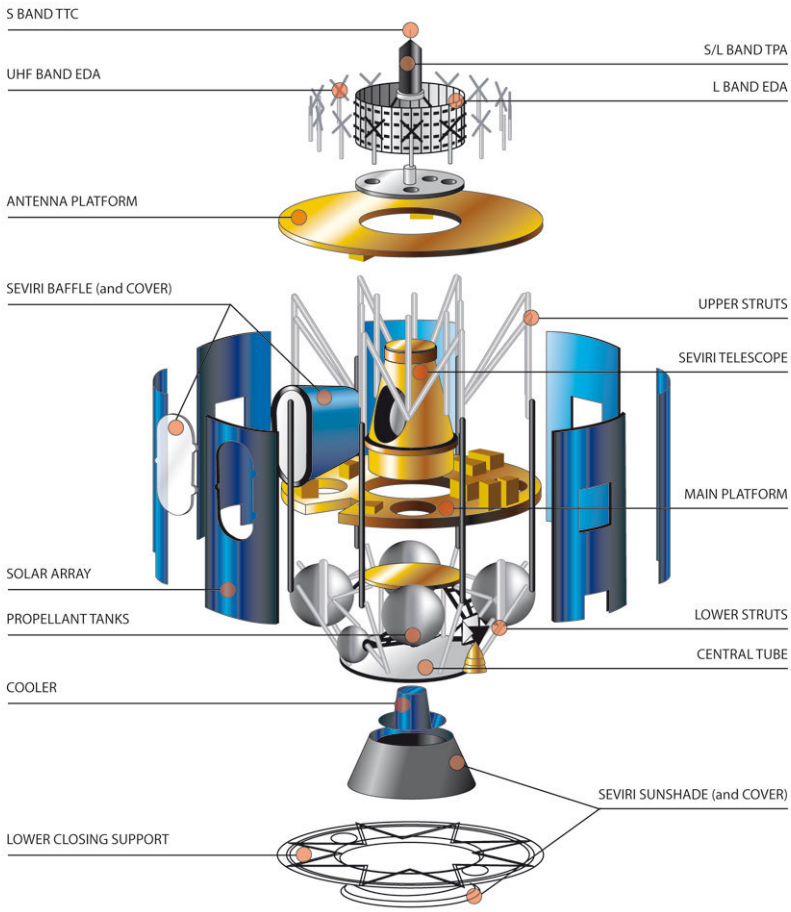

Figure 3 *Schematic picture of the geostationary MSG satellite which has the SEVIRI instrument on board. Image ©EUMETSAT 2020*

preferred to the completeness of the coverage. **Paper III** and **Paper IV** describe the background of the work in a larger context and **Paper V** touches on the practical side of the snow research.

The author gained practical experience of snow measurements in the Snow Reflectance Transition Experiment (SNORTEX) campaign near Sodankylä, Finland during the winters 2008–2010 when he took part in snow measurements *in situ* (e.g., snow pit measurements). Some of these measurements are described in **Paper V**. The SNORTEX campaign is described in more detail in Manninen and Roujean (2014). During the SNORTEX campaign, aerial photos were taken by a directly downward-pointing automatic camera system described in Manninen et

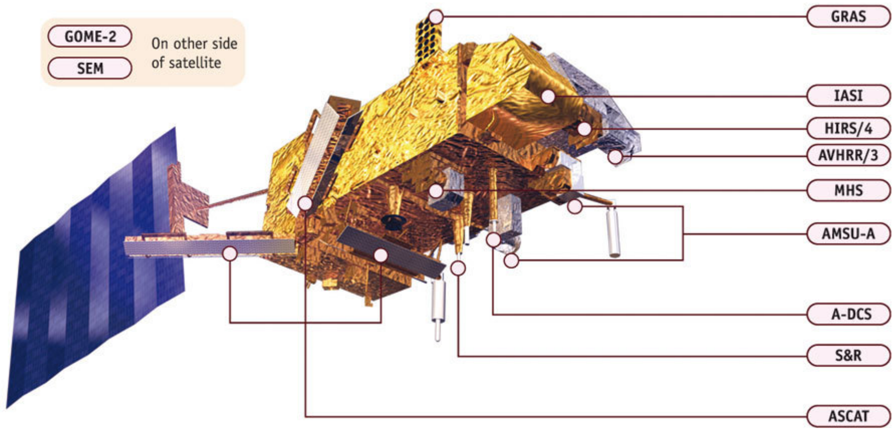

Figure 4 *Schematic picture of the polar-orbiting Metop satellite which has many instruments onboard. Only the AVHRR/3 instrument is relevant in this work. Image ©EUMETSAT 2020*

al. (2009) and Manninen et al. (2012). Some of these photos are shown later in Figs. 6, 8, 10 and 11 which present examples of the different features of the snow cover.

Before SNORTEX, the author participated in an aerial measurement campaign in Sodankylä in spring 2004. It was an especially educational experience to see the complexity of the snow cover from a helicopter flying at different altitudes. During that campaign, the author took photographs which illustrate the typical features of the snow cover in boreal forests which must be taken into account when developing satellite snow products.

In situ observations from weather stations can be complemented by a wide spectrum of snow measurements made during snow measurement campaigns. **Paper V** describes snow surface roughness measurements which were made as part of the SNORTEX campaign. Some experiments to measure snow coverage using different methods were also made during and after SNORTEX, but these results have not been published.

Two of the SAFs are relevant for this work. At first, snow products were developed by Swedish Meteorological and Hydrological Institute (SMHI) in the LSA SAF which is still processing the products described in **Papers I** and **II**. During the development of the first version of the MSG/SEVIRI snow product, FMI took over the responsibility of these snow products. **Paper III** gives a general view of the LSA SAF after the first products, including one snow product (MSG/SEVIRI, Version 1), had reached operational status. The paper also presents validation results based on comparison with the NOAA/NESDIS IMS product, which were updated for a slightly longer period in **Paper IV**. Later, all LSA SAF snow products were transferred to H SAF even though the processing and distribution of the transferred products remain in the LSA SAF.

Paper IV presents comparison results of several snow products based on satellite data and NWP model analyses before the development of the products described in **Papers I** and **II**. In that paper, two pure satellite snow products (MODIS and MSG/SEVIRI, Version 1), two NWP snow analyses (European Center for Medium-Range Weather Forecasts (ECMWF) and HIRLAM) and the IMS snow product were compared. The results suggested that NWP snow analysis would greatly benefit from satellite-based snow cover information.

The targeted users of the snow products developed in the LSA SAF were NWP and other meteorological applications. Discussions with NWP experts confirmed that they prefer uniform single instrument products that do not employ other data sources, such as surface observations. This has been kept in mind during the development of the H31 and H32 products. Often, these requirements exclude snow products which are calibrated by surface observations (e.g., SWE).

The first version of the MSG/SEVIRI snow product was a simple by-product of cloud masking, which had practically no room for improvements in the snow detection. The idea of an empirical approach (described in more details in Chapter 3 and **Paper II**) to the satellite snow detection had been formed and the algorithm development started before the writing of **Paper IV**. The second redesigned version of the MSG/SEVIRI snow detection algorithm (and operational code) was developed in 2007. The necessary review process of operational products with validation is time-consuming and the second version did not reach operational status until April 2009. This product is currently available as H SAF H31 (MSG/SEVIRI) snow extent product and is described in **Paper I**.

A similar snow detection product was planned for the Metop satellites. The first Metop satellite reached operational status in May 2007, but the development of the Metop/AVHRR product did not start until some time after the MSG/SEVIRI product reached operational status. The same development philosophy was used and the production of the current H SAF H32 (Metop/AVHRR) snow extent product started in 2016. The year 2015 was backprocessed. Operational status was reached in July 2018. This product and validation results based on weather station data are presented in **Paper II**.

In the following chapters of this thesis, the focus is on the empirical approach to satellite snow detection development described in **Papers I** and **II**.

2 A VIEW FROM ABOVE

The introductions of **Papers I** and **II** describe shortly the characteristics and the difficulties of the snow cover measurements from the viewpoint of the satellite snow product developer.

Snow cover is highly variable both in time and space. The photo in Fig. 5 shows many typical variable features that complicate snow detection. First, there are scattered clouds and shadows of clouds, which can be a source of misclassifications, especially in cases when small clouds cover parts of the grid cell. Secondly, the patchwork of fields, forests and towns create small scale variability which is easy to recognize in high-resolution images such as aerial photos, but in lower resolution weather satellite imagery these small-scale features blend into each other.

In general, much of the surface variability is in the scales much smaller than

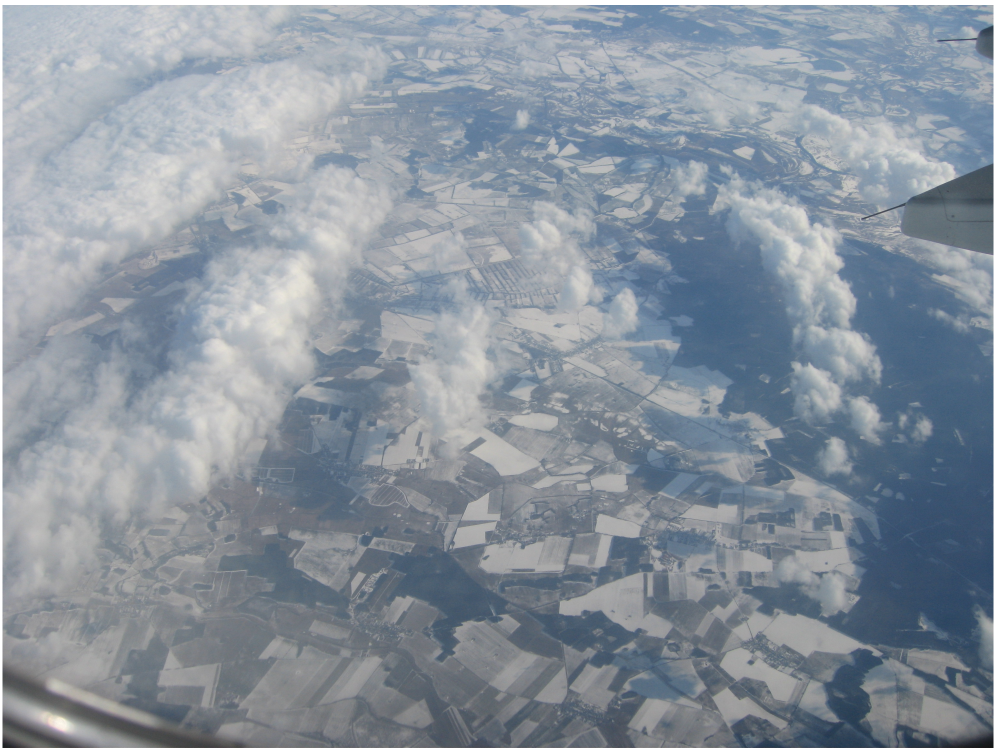

Figure 5 *Aerial view of the snow-covered landscape in Germany in March 2006. The photo shows the highly variable and almost chaotic nature of the snow-covered view seen from satellites. Many features complicating the snow detection are present, such as clouds, shadows, variable vegetation and forests. Photo: NS.*

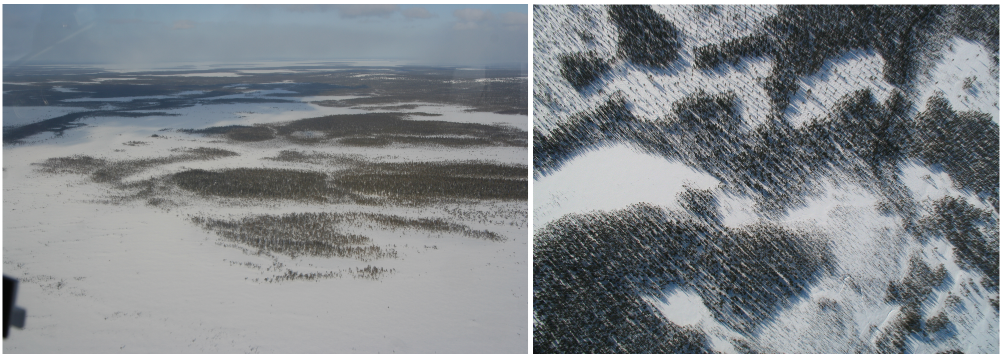

Figure 6 *The size of the trees and tree densities vary in forests. A single satellite pixel is usually a mixture of forests, fields, lakes and other land cover types. Photo: left NS, right FMI.*

satellite resolution (Metop/AVHRR 1 km at nadir, MSG/SEVIRI 3 km at nadir), especially when the satellite is near the horizon. The surface inside one satellite pixels is practically always a mixture of open areas, forests, lakes and built-up areas when larger water bodies are excluded. This is especially relevant for geostationary satellites, such as MSG, because much of the seasonal snow is near the edge of the detection disk where the resolution can be much lower (about 6 km in Britain and about 10 km in Southern Finland for MSG/SEVIRI). Still, there is annual seasonal snow in the flatland areas in lower latitudes in the Middle East, the Tibetan Plateau and, as an example from Africa, in Lesotho in southern Africa (Wunderle et al. 2016), which snow cover algorithms should detect.

Forests are highly variable in themselves (see e.g., Crowther et al. 2015). There are many kinds of trees which form the canopy and changing understory with twigs and shrubs. Sometimes trees grow in dense forests, but in other areas, trees are sparse and even then small in size. Deciduous forests are often practically transparent from satellites during the winter when trees are leafless, but evergreen forests can prevent snow detection almost completely. The photos in Fig. 6 present the effect of variable forest density and tree size in Finnish Lapland. The effects of the vegetations, especially the forest canopy, are discussed in Manninen and Jääskeläinen (2018) where they show that snow is darker at the forest floor than in open areas even when the snow itself is not different. This effect is visible in the photo presented in Fig. 11.

Two especially interesting phases of the seasonal snow cycle from the snow detection point of view are new snow on bare ground and the melting season when bare patches start to appear in the continuous snow cover. New snow layers may be very thin and may not cover the surface completely. This is especially

Figure 7 *New snow layers are often thin and uneven (photo on the left and top right). Snow cover is especially variable during the melting season when small- and large-scale melting patterns mix and some areas are completely snow-free and others are still almost fully snow-covered (two photos on the right, middle and bottom). Photos: NS.*

common in very rough areas where snow tends to accumulate in sheltered spots or near obstacles during windy weather, but even on grass unevenness can be seen (examples in Fig. 7, left and top right). When snow melts, the first snow-free patches are often the thaw circles which form around obstacles such as tree trunks and stones (seen in the top left in Fig. 8). Snow melts faster also on sunny slopes. Melting continues unevenly until snow can be seen only in some sheltered cold spots or in places where larger amounts of snow have accumulated. This can

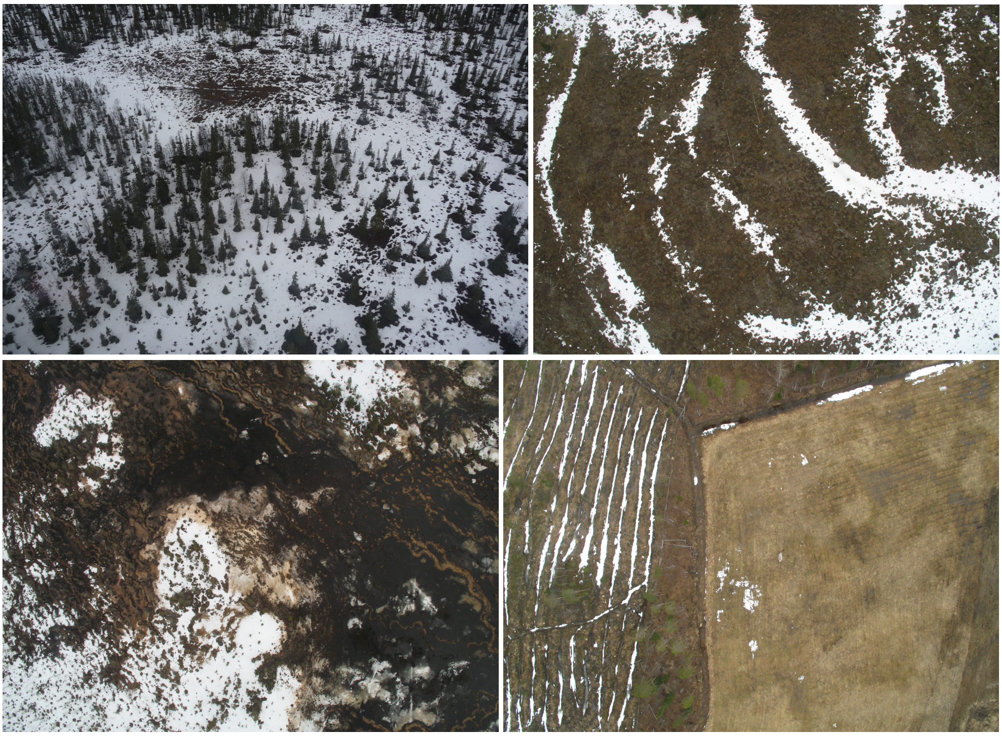

Figure 8 *Melting patterns seen from a helicopter. Note the melt patches around the tree trunks on the top left photo and melting water covered bog on the bottom left. Snow in ditches is the reason for the striping in the bottom right photo. Photos: FMI except top left NS.*

be seen quite well in the bottom right photo in Fig. 8, where snow in ditches is seen as white stripes. During the melting, meltwater can cause local flooding and sometimes, especially in wetlands near lakes and rivers, a mixture of snow and water can cover large areas (example in Fig. 8).

Another reason for the variability is the snow on trees. Examples are shown in the photos in Fig. 9. This phenomenon is often short in duration because temperature changes and wind can clear the trees soon after the snowfall, but at least some snow may stay on trees even days or weeks. Snow on trees can have a significant role in the snow detection when evergreen canopy is covered by snow, but it also has a role in deciduous forests when the snow sticks on the tree trunks and branches.

Much of the variability is on the surface itself but parts of the variability are more or less related to the observing technology (viewing angles, resolution). In

Figure 9 *Snow on trees. In the top right and middle, evergreen trees, in the top left and bottom, deciduous trees. In the top right, so-called tykky which forms in special conditions covers fir trees almost completely. Example of snow stuck on the tree trunks in the photo below. Photos: top right Pirkko Pylkkö, others NS.*

Figure 10 *The viewing angle changes the view from satellites. In nadir, trees cover only the small area under the tree, but when seen from angles near the horizon, the surface area obscured by one or more trees is much larger. The area directly under the tree is not visible in nadir, but not covered when seen from a higher angle. Photo: FMI.*

addition, there are large-scale features, which limit the use of optical remote sensing (clouds, darkness). Even though satellites detect the surface from high altitudes (Metop about 817 km and MSG about 35786 km), the viewing angle can be quite high near the edge of the swath (polar satellites) or near the edge of the detection disk (geostationary satellites). One characteristic difference between geostationary and polar satellites is that the former always see a certain location from the same angle while the latter observe the surface from a different angle every time. The significance of the viewing angles is illustrated by the photo in Fig. 10 where the trees near nadir cover only a small area directly under the tree while the trees away from nadir cover bigger area behind the tree but the area just under the tree is visible. At very low angles, there may be many trees between the camera (or radiometer) and the surface.

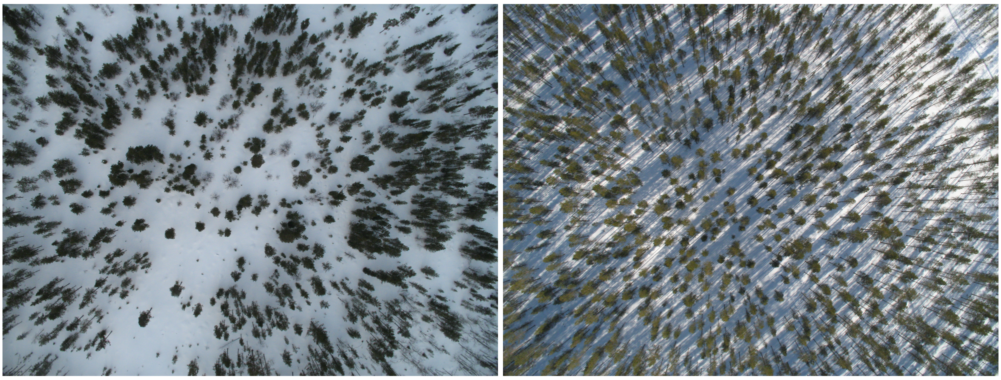

Figure 11 *Photo on the left shows that in cloudy conditions snow cover between trees is evenly grey or white. The darkening effect between trees in dense spots is also visible. However, in clear sky conditions which are required for optical satellite snow detection, shadows of the trees create highly variable lighting over the snow cover (photo on the right). Photos: FMI.*

Satellite instruments using optical and IR channels for snow detection require clear sky conditions. As shown in the photo in Fig. 5, clouds cover the surface and prevent snow detection. Sometimes thin cloud layers are transparent and snow detection may be possible, but this may be difficult to achieve by automatic algorithms. On the other hand, cloud-free conditions during the day mean that there are shadows. Especially in high latitudes where the sun is near the horizon during the snow season, shadows can cover much of the surface as seen in Fig. 11.

The use of the optical instruments requires that the surface is illuminated. This is a serious problem during the winter when long nights make the snow detection difficult or impossible in snow-covered polar regions (see Fig. 12) even in cloud-free conditions. There are some instruments (e.g., VIIRS onboard Suomi-NPP and JPSS satellites) with special day/night channel, which may have potential for nighttime snow detection together with other channels used for removing fog and clouds. At the moment, such channels are not planned for EUMETSAT satellites.

Figure 12 *Moon shining during the polar night in Muonio, Finland. Snow-covered surface is visible, but the moonlight is not bright enough for the instruments used in the algorithms presented in this work. In the future, satellite snow algorithms may employ day-night band data provided by some instruments, such as VIIRS. Photo: Merikki Lappi.*

3 ALGORITHMS

3.1 EMPIRICAL APPROACH

The H31 and H32 snow products have been developed for meteorological applications, especially NWP. The main principles considered during the development were:

directness Snow cover classification is done first without any kind of preceding cloud masking which could introduce additional limitations and even errors to the snow detection algorithm. The algorithm aims at finding snow-covered and snow-free pixels, other pixels are set as unclassified.

accuracy Snow cover classification aims at accuracy instead of coverage. While in many other applications, large coverage is preferred, this approach is preferred by the NWP community (C. Fortelius and L. Rontu, personal communication at FMI).

single-source data Only satellite data from a single instrument will be used. Limited use of static data (such as land cover classification) and other products based on the same instrument and processed in the same system (such as LSA SAF LST) is possible.

In the Introduction, some of the features and phenomena which make the satellite snow detection a rather complicated task were described. The complexity of the snow cover suggests that there are no simple analytical methods for snow detection which work in all areas and in all snow cover conditions. Thus, an empirical approach may be more appropriate and better suited for satellite snow detection. However, the empirical approach requires much more work at the start of the development process, because there must be observations which are the basis of the algorithm.

The empirical approach means that the product is not based solely in such concepts as NDSI or similar simplified ways to distinguish snow-covered and snow-free surfaces or clouds, as there are lots of borderline cases, which may not be classified correctly by such methods.

As described in **Papers I** and **II**, the development of both algorithms was started by creating a subjectively classified data set using the data from the instrument for which the algorithm will be developed. These development data sets were created by manually classifying a large number of pixels in satellite images to different classes and then collecting all available data from those pixels (radiances, brightness temperatures, land use, sun and satellite angles etc). This development data set can then be analyzed in many ways to find out the best ways to detect snow and snow-free pixels. The development data sets created consist of a large number of manually classified pixels. The MSG/SEVIRI data set has about 509,000 and the Metop/AVHRR dataset about 609,000 classified pixels which cover different land cover types, different snow conditions and different cloud-covered pixels.

3.2 PROCESSING CHAIN

A generalized flow chart of the H31 and H32 snow product generation is presented in Fig. 13. As the aim was to develop a daily snow detection product, the product generation was split into two phases. The first phase (SC1) is the snow detection in a single satellite image. In the case of H31, this single image product is generated every 15 minutes for the full MSG/SEVIRI disk. Every day there will be 96 single image snow products covering the same area. In the H32 product, the single image product is generated every three minutes for each Product Dissemination Unit (PDU). During one day, there are 480 such images, which cover practically the whole surface of the Earth.

The second phase (SC2) consists of the necessary operations needed to combine single image products into one daily snow extent product. For the H31, this means counting the different classifications in each pixel in all 96 images and then deciding the final daily classification for each pixel. This is a straightforward process, which is described shortly in Table 3 in **Paper I**.

For the H32, the process required for the generation of the global daily product is slightly more complicated because every PDU snow product covers a different part of the globe. The daily product is created by reprojecting each PDU product pixel from oldest to youngest to the 0.01×0.01 degree lat-lon grid and then applying some smoothing based on 3×3 pixels around each pixel in the lat-lon grid (see details in Table 4 in **Paper II**).

Production in two phases has the additional benefit of flexibility which was not anticipated at first. Even though the original requirement described in the project documentation is to produce daily products in predefined grids (satellite grid for H31 and global lat-lon grid for H32), intermediate SC1 products can be used to generate additional or tailored products for specific users. For example, the intermediate H32 SC1 product can be used to produce “snow barrels” i.e. 10×10 pixel distributions which may be better suited for NWP data assimilation, but the feasibility studies are still underway.

Both H31 and H32 are produced in the LSA SAF processing environment. Products are distributed via EUMETCast and are also available from the LSA SAF website in HDF5 format.

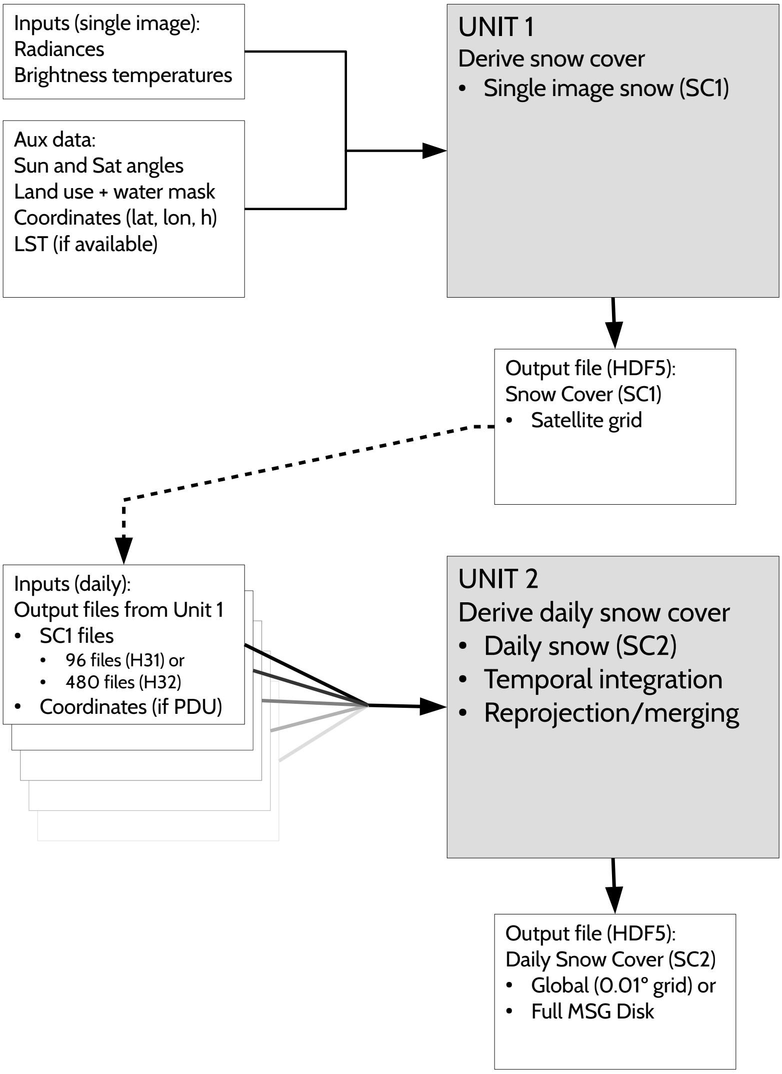

Figure 13 *Simplified flow chart of the processing of the H31 (MSG/SEVIRI) and H32 (Metop/AVHRR) snow products. In both versions, single image snow products (SC1, mainly for internal use) are produced when new images are available (every 3 minutes for H32 and every 15 minutes for H31). At the end of the day, single image products are merged and daily snow cover files (SC2) are produced, distributed and archived.*

3.3 ALGORITHM DEVELOPMENT

In the LSA SAF production system, radiances and brightness temperatures of different channels are readily available. When the algorithm development started, the development data was collected from these files without converting the data to reflectances. Because practically all of the classification rules are based on channel ratios or ratios of channel differences, this perhaps poor choice was not fatal and the algorithm development was successful. Later, when the H32 algorithm was modified for testing purposes to use the AVHRR Global Area Coverage (GAC) data, reflectances were converted to radiances and the modified algorithm could be used successfully.

The development data sets were analyzed and visualized so that classification rules could be developed. Fig. 14 from **Paper I**, shows one way to present the collected data. The data can be presented as 2D and 3D plots of channel ratios, channel differences or any other combination of collected data so that methods

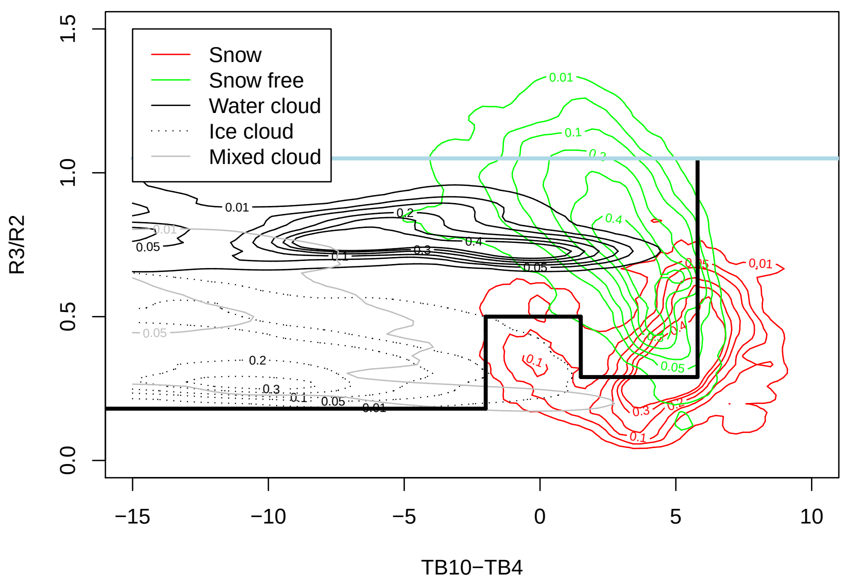

Figure 14 *Example of the probability densities of the scatterplots based on the development dataset for MSG/SEVIRI (radiance ratio R_3/R_2 vs brightness temperature difference $\Delta T_B = T_{B10} - T_{B4}(\mathrm{K})$). The thick black and blue lines show thresholds for SNOW (black) and NO SNOW (blue), based on the rules used in the MSG/SEVIRI algorithm. SNOW: rules (R9)–(R12) and NO SNOW: rule (R14) as described in **Paper I**. (Excerpt of Figure 1 in **Paper I**).*

separating different classifications can be found. The example in Fig. 14 shows a 2D probability density plot of the brightness temperature difference of the SEVIRI channels 10 and 4 and radiance ratio of the channels 3 and 2 (see Table 1).

Use of the MSG/SEVIRI channels 2 and 3 is based on the differences of the spectral properties of snow and clouds on these channels in a similar way as in NDSI. Similarly, the brightness temperature difference of channels 10 and 4 helps in separation of snow and clouds. As can be seen in the figure, different classifications have some overlap, but different clouds, snow free surface and snow covered surface typically have different distributions in this plot. The black and blue lines in the figure present some of the classification rules relevant to this density plot. Other rules are needed to improve the classifications in overlapping cases.

During the development, different algorithm candidates were used to create snow cover images which were then compared to RGB images or sometimes to other satellite products to find out any kind of misclassifications. In some cases, Google Streetview images were used to see the surface features present in the area. Based on the results, the algorithm candidate was modified so that the classifications could be corrected or, in some cases, completely removed. The stable and final SC1-phase algorithm versions consist of 21 and 23 rules for the MSG/SEVIRI and Metop/AVHRR products, respectively.

During the development of the SC1 algorithms, the development of the daily algorithm was also started. The algorithm used to merge single image SC1 products to create the daily H31 MSG/SEVIRI product consists of 7 rules. For the daily H32 Metop/AVHRR product, the SC1 products must first be reprojected to a global grid and then smoothed using an algorithm consisting of 12 rules.

The complete snow extent algorithm consisting of the single image and daily parts for the H SAF MSG/SEVIRI H31 product is presented in **Paper I** and for H SAF Metop/AVHRR H32 in **Paper II**. They are also described in the official product documentation available on the LSA SAF and H SAF websites.

Examples of the H31 and H32 products for March 22, 2019, are shown in Figs. 15 and 16, respectively.

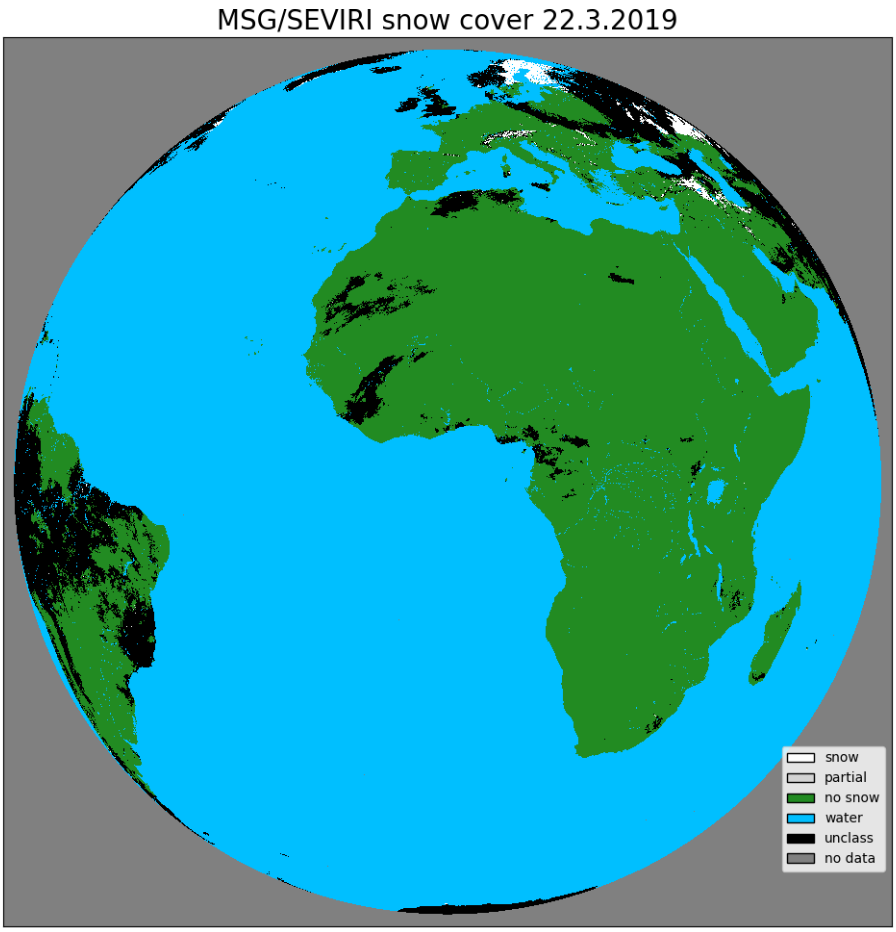

Figure 15 *Example of the daily H31 product for March 22, 2019.*

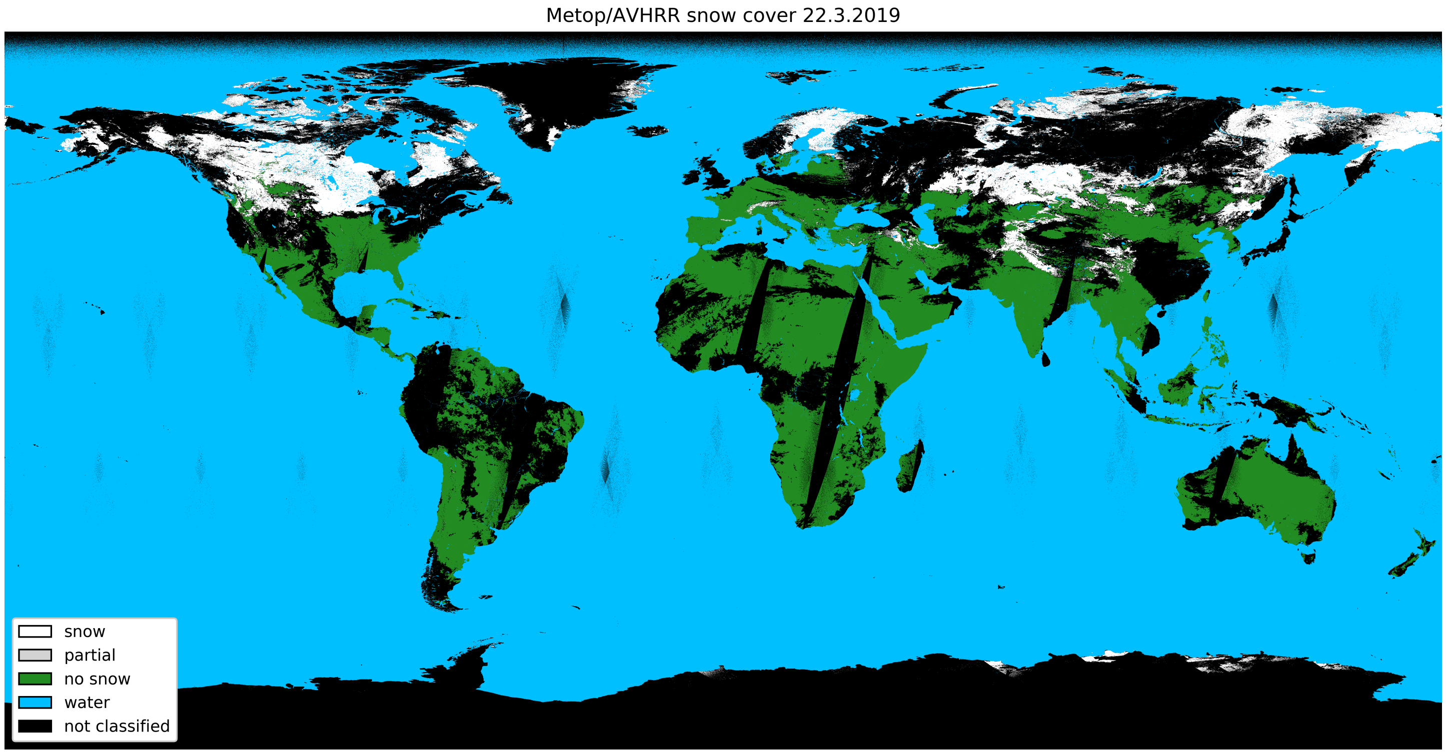

Figure 16 Example of the global daily H32 product for March 22, 2019.

4 VALIDATION

4.1 OBSERVATION SOURCES

Validation is an essential part of the development of operational products. Validation is needed to confirm that the product is valuable, provides reliable information and meets the requirements for operational use. The major challenge in the validation of any snow-coverage product is the lack of easily available observations of the snow coverage, especially in areas where snow cover is not continuous. For further development and better validation, observations of the snow (or lack of snow) on canopy would be valuable, but such observations are even more difficult to obtain.

The best option for any satellite product validation would be high-quality *in situ* observations. Thus, for satellite snow extent or fractional snow cover products, observations of the snow coverage (percentage of the snow-covered surface or similar) would be the best choice. Unfortunately, such datasets are not available operationally i.e., in high temporal resolutions (preferably at least daily) and from large areas. Such observations would be invaluable when the edge of the snow-covered area is searched.

There are at least two possible solutions for this lack of observations. One can use observations from the synoptic weather stations which do not measure snow coverage, but usually provide at least snow depth observations and sometimes the state of the ground observations which are rough estimates of the snow coverage. The other option could be a measuring campaign, where some methods for measuring or estimating snow coverage can be used.

One validation option would be the use of other satellite snow products, but this option is not completely satisfactory. Even when the product under validation matches the baseline product closely, there is no way of knowing which of the products is more correct in areas where the products differ. This method was used in **Paper I**. Also the use of weather model snow analysis has been considered (see also the **Paper IV**). If in the future satellite snow products will be used in the weather model analysis, this may not be a suitable data source for validation as the validation data is not completely independent of the satellite product.

During this work, many ideas for snow coverage measurements were considered, tried and rejected for different reasons. Some of the ideas tried in practise were:

knotted string In this method, a 100 m string has markings at 1 m intervals (knots). The measuring team pulls the string in a straight line and counts snow-covered and snow-free points. This may be repeated several times in slightly different spots to improve the number of observations in each site. These counts must then be converted to coverage estimates. The method is rather expensive (labour costs) and time-consuming.

drones Aearial images from drones provide high spatial resolution (< 1 m) data about snow coverage, but analysis of the snow coverage requires either lots of manpower or a high-quality snow detection algorithm for the drone photos. Collecting daily drone imagery from large areas is also challenging.

moving car One way to gather snow coverage observations is a car-based observation team. An observer can estimate the average snow coverage from a moving car at small intervals (e.g. 30 seconds) and save the estimated value using an automated system which saves the GPS coordinates, time of each observation and perhaps photos for later checking of the estimates. This method needs a two-person team of driver and observer and has some biases which may be difficult to avoid or correct. The snow cover near the roads is never natural (snow ploughed from the road, faster melting) and especially in forests, it is difficult to estimate the snow coverage far away from the road. However, this method has some potential because it can provide a large number of observations from relatively large areas. With some development and improvements, this method could produce additional regional validation data.

social media Photos in social media have been used successfully as meteorological observations (Hyvärinen and Saltikoff 2010). There are tools which can be used for fast selection and classification of suitable images, but there are many issues which may make the use of social media photos cumbersome such as privacy and copyright requirements or location and timing inaccuracies.

crowdsourcing Weather (including snow) observations could be collected using mobile applications. E.g. the FMI Weather app includes this capability, but currently, snow coverage is not one of the observation types supported. The reliability of crowdsourced observations is also uncertain because the observers are usually untrained and sometimes even malicious.

The best coverage for validation can be achieved by using weather station observations as described in section 3b (Surface observations for validation) in **Paper II**. In short, the surface observations of snow depth and the state of the ground are converted to binary form (snow/no snow) and partial coverage is handled separately by converting partial values to snow-free or full snow cover. Partial snow cover cases can also be excluded from the validation. All three options were tested and the results presented in **Paper II**.

4.2 VALIDATION MEASURES

The validation measures are calculated using the counts of cases on the contingency table shown in Table 2. Following the terminology of Jolliffe and Stephenson (2012), cases where the satellite detected snow are either Hits, a, when the satellite correctly detected snow, or False Alarms, b, when surface observation does not report snow. Similarly, cases where the satellite detected snow-free surface are either Correct Rejections, d, or Misses, c, when surface observation shows the presence of snow.

However, the snow cover has a strong seasonal cycle, and during the northern summer, there are relatively few snow observations compared to no-snow observations, which means that d is much larger than the other values. The validation of snow products is complicated, because in the cases where one category dominates, the most common validation measures degenerate to trivial values.

A quite comprehensive list of validation measures is presented in Hogan and Mason (2012). The validation measures used and their behaviour when d dominates are described below (and in **Paper II**).

One of the most commonly used validation measures Proportion Correct

$$\mathrm{PC} = \frac{a+d}{a+b+c+d},$$

tends to 1 if d dominates. For other measures, this might not be as self-evident, but can be seen when the measures are shown as the function of two conditional probabilities Hit rate, (H)

$$H = \frac{a}{a+c},$$

and False Alarm Rate (F)

$$F = \frac{b}{b+d},$$

Table 2 *Contingency table of the comparison between two categorical snow analyses. The symbols a-d represent the number of cases in each category.*

	Analysis 2 (baseline)	
Analysis 1	Snow	No snow
Snow	a (Hit)	b (False Alarm)
No snow	c (Miss)	d (Correct Rejection)

and the base rate (s)

$$s = \frac{a+c}{a+b+c+d}.$$

In the perfect analysis, H should be 1 and F should be 0.

Now PC is

$$\mathrm{PC} = (1-F)(1-s) + Hs,$$

and dominating d implies $s \to 0$ and $F \to 0$, so PC tends to one using this notation also, as it should.

Slightly counter-intuitively, the often-used replacement for PC, Critical Success Index, which ignores Correct Rejections and is therefore used in cases when d dominates, also degenerates. Its definition is

$$\mathrm{CSI} = \frac{a}{a+b+c} = \frac{H}{1+F(1-s)/s},$$

and when there are very few snow observations ($s \to 0$), CSI will tend to zero. Also the Heidke Skill Score (the PC corrected for random hits)

$$\mathrm{HSS} = \frac{2(ad-bc)}{(a+c)(c+d)+(a+b)(b+d)},$$

will tend to zero. On the other hand, the False Alarm Ratio (FAR)

$$\mathrm{FAR} = \frac{b}{a+b} = \left[1 + (\frac{s}{1-s})\frac{H}{F}\right]^{-1}$$

will tend to one, while in the perfect analysis it should be 0.

BIAS is used quite commonly in validation. It is defined as

$$\mathrm{BIAS} = \frac{a+b}{a+c} = \frac{(1-s)F}{s} + H,$$

which in the perfect analysis should be 1. It is not affected by dominating d.

A measure that does not degenerate is the Symmetric Extremal Dependence Index (SEDI)

$$\mathrm{SEDI} = \frac{\ln F - \ln H + \ln(1-H) - \ln(1-F)}{\ln F + \ln H + \ln(1-H) + \ln(1-F)}$$

that in the perfect analysis should be 1. The SEDI can be used to assess whether there is a real drop in quality of the snow product in summer or is it because of the characteristics of the validation measures used. If either F or H is zero or unity, SEDI is not defined. When either F or H was zero, a very small number (0.0001) was added to the numerator and denominator in the calculation of H and F. This was done purely for visualization purposes so that all cases would be plotted in Figs. 17 and 18.

4.3 VALIDATION RESULTS

In **Paper II** (Figs. 5–7), validation results are presented only for the Metop/AVHRR product, but the same validation procedure was also applied to the MSG/SEVIRI product from 2013 onwards. Before that, there were no easily available snow observations in the FMI observations database. The results of the validation are presented in Figs. 17 and 18 for the validation option where partial snow is converted to snow-free.

Subplots of both figures present time series of different validation measures. On the top left, the daily number of snow pixels is shown in light blue. When one correct classification dominates, even a small number of misclassifications can cause unexpected behaviour and emphasize misclassifications unnecessarily. For this reason, daily values are colour-coded: dark green data points mark the days where $d \leq 20(a+b+c)$ i.e., the proportion of correct snow-free observations is not too large, light green marks the days when $d > 20(a+b+c)$ and orange the days where d dominates ($d > 200(a+b+c)$). In practice, this erratic behaviour happens during the northern summer when seasonal snow cover in the well-lit regions is at its minimum.

Even a single misclassification caused by, for example, a thunderstorm, certain surface features or even unrepresentative surface observations, can change the results significantly even when practically all other classifications are correct. This can be seen quite well in PC and F, which show that the results are nearly perfect in these days even though more sophisticated measures, such as the HSS may show much more variability. When the winter begins in the Northern Hemisphere, the snow-covered area becomes larger and the number of Hits, a, grow and Correct Rejections, d, decrease, the validation measures stabilize and improve greatly and stay at a high level most of the winter and spring.

Even though misclassifications are relatively rare, during the northern summer they do show in some of the validation measures. Both products (H31 and H32) provide excellent results during the northern winter and spring when the snow cover has the highest potential impact on weather, but the results are still very good even during the summer considering that SEDI is still reasonably high.

These surface observation-based validation results strongly suggest that the empirical approach used in the MSG/SEVIRI and Metop/AVHRR snow extent products can produce reliable snow coverage data, especially during the northern winter and spring.

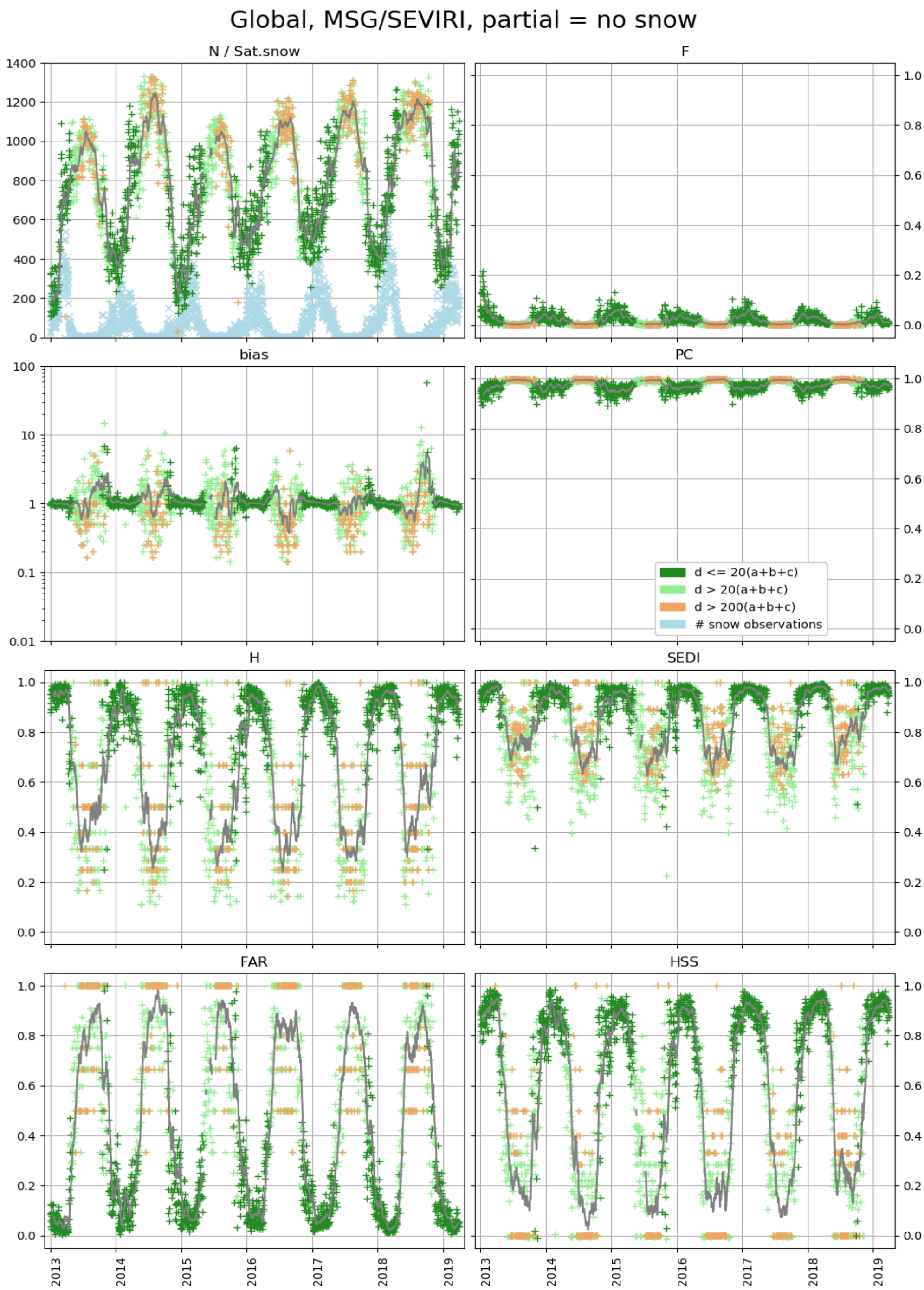

Figure 17 *MSG/SEVIRI (H31) validation measure time series, partial classifications converted to snow-free. Each day is colour-coded to indicate whether the proportion of correct snow-free observations is so large that most of the validation measures degenerate (indicated by light green and in the most extreme cases by orange). Light blue marks the number of satellite snow observations per day.*

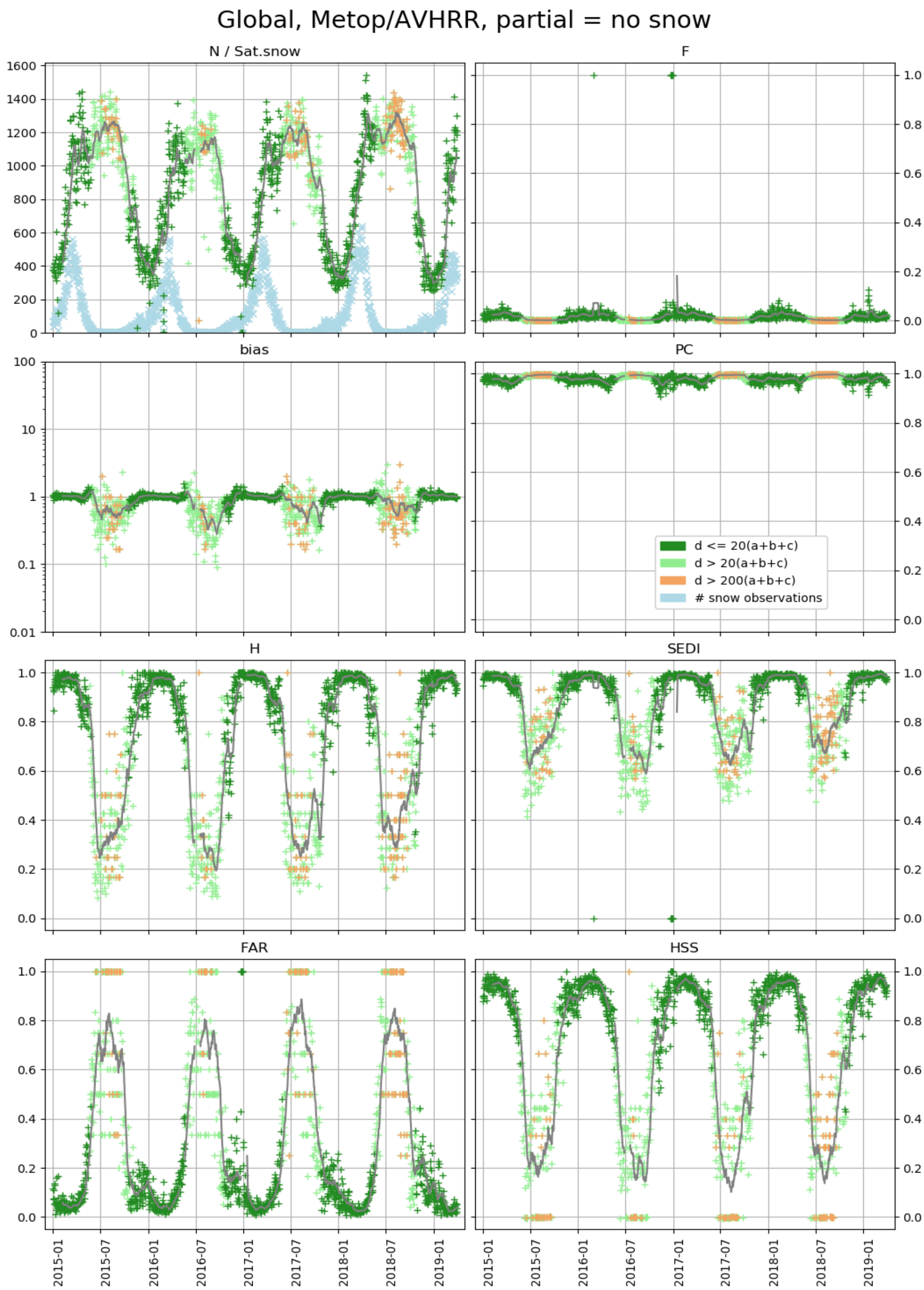

Figure 18 *Metop/AVHRR (H32) validation measure time series, partial classifications converted to snow-free. Each day is colour-coded to indicate whether the proportion of correct snow-free observations is so large that most of the validation measures degenerate (indicated by light green and in the most extreme cases by orange). Light blue marks the number of satellite snow observations per day.*

5 FUTURE

Snow extent products, such as the ones presented in this work (**Papers I** and **II**), may be well suited for NWP data assimilation even though snow extent products do not provide direct data about SWE or snow depth. Neither of the snow products presented in this work have been assimilated in the operational NWP, but there are at least two ongoing projects which aim for operational snow data assimilation. In the Met Office, the work is nearing operational status (Pullen et al. 2019). At FMI, a variant of the Metop/AVHRR H32 product is in the assimilation trial phase, where so-called "snow barrels" have been used to create artificial snow observations which are then going into the assimilation system along with the weather station observations.

The MSG/SEVIRI and Metop/AVHRR algorithms are developed for EUMETSAT satellites and they are only used operationally to process data from EUMETSAT-operated satellites (MSG and Metop). The SEVIRI instrument is only onboard MSG satellites, but different versions of the AVHRR instrument have been used also on NOAA operated satellites. Currently, the Metop/AVHRR algorithm relies on the availability of the channel 3A, which is only available on AVHRR/3, first onboard NOAA-15 launched in 1998. The current algorithm has been successfully modified to use reflectance data based on AVHRR GAC data. The current operational algorithm or the modified reflectance-based version could be used to process all AVHRR/3 data, but processing scenes without channel 3A requires more work.

The next generation of EUMETSAT satellites will supersede the current MSG and Metop satellites in the early 2020s. The MSG series satellites will be replaced by the Meteosat Third Generation (MTG) with the Flexible Combined Imager (FCI), which has 16 channels (SEVIRI has 12 channels) and better resolution (1 km instead of 3 km at nadir). The Metop satellites and the AVHRR instrument onboard them will be superseded by Meteorological Operational Satellite - Second Generation (Metop-SG) with the new Meteorological Imager (METimage) which is a considerable improvement (20 channels) on rather outdated AVHRR (6 channels, 5 in simultaneous use). It also has better resolution (500 m instead of 1 km at nadir).

A similar empirical approach will be used to develop snow extent products for these new satellites. The first MTG/FCI launch is planned for 2021 and Metop-SG/METimage launches from 2022 onwards.

High-quality *in situ* snow coverage observations would be valuable in satellite snow product development. New ways to measure snow coverage either in campaigns or operationally would benefit the development of satellite snow products.

6 CONCLUSIONS

Snow is one of the key components of the global climate system. It has a strong influence on energy transfer, temperatures and many ecological features, but it also has a large impact on societies when it comes to water security, energy production and traffic. Snow cover changes are an important part of the climate change.

In NWP, Satellite-based snow products can improve snow analysis and this may help to improve weather forecasts at least on the local level. Dedicated snow products for meteorological applications are valuable in NWP.

The main contributions of this thesis are:

- The empirical approach has been used for satellite snow product development. This approach takes into account the natural variability of the surface features such as vegetation and the snow itself.

- Two snow detection algorithms and products based on them have been developed. Both products have reached operational status and are freely available.

- Both products have been validated using reliable surface observations. Validation results show that both products estimate the snow cover extent accurately. The surface observation-based validation period for the MSG/SEVIRI product is over 6 years and for the Metop/AVHRR over 4 years.

- Preferences of the NWP community have been considered and taken into account in the product development. The target is reliable snow detection where accuracy is preferred to coverage, i.e., it is better to avoid misclassifications than unclassified pixels.

Especially important for the future of these and similar products is that there are people and organizations which use the products. When the operational satellite products aim for NWP applications, there are two relatively time-consuming phases. Both operational product development and changes in NWP systems require careful testing before changes can be made in the operational system. It is, therefore, very positive that both snow products have found interested users. The MSG/SEVIRI product has been tested actively at Met Office and it seems likely that operational use in NWP analysis will begin during 2020. The polar Metop/AVHRR product reached operational status 2018 and there are now ongoing trials at FMI where the feasibility of the Metop/AVHRR product is studied. For these trials, a new product version based on the intermediate version (SC1) of the Metop/AVHRR product has been provided.

No product is perfect. There are always misclassifications which should be removed by algorithm improvements. Algorithm improvements may allow classification of the cloud-free pixels which are not classified by the current algorithm. Especially, partial snow cover at the edges of the snow-covered area needs more attention. For that, more and better surface observations of the snow coverage are needed.

New satellites and more powerful computers may allow the development of better snow detection algorithms. Development data sets must still be collected by hand, but machine learning and other artificial intelligence methods may benefit the algorithm development.

Validation will always be an integral part of the product development and for that good coverage of reliable high-quality surface observations are essential. New methods for measuring snow coverage are needed urgently.

While the focus of this work is in the development of operational snow detection products for operational applications, the scientific side of this work is not negligible. **Paper I** has been cited 26 times at the time of writing and **Paper III**, which describes LSA SAF and its products, has been cited 115 times.

Even though this work is only a part of a larger picture, the empirical approach to satellite snow detection has potential for future applications.

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